

# **PERFORMANCE OF GLOBAL POSITIONING SYSTEM BLOCK II/IIA/IIR ON-ORBIT NAVSTAR CLOCKS**

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## **Abstract**

*Analysis of the performance of all on-orbit Navstar space vehicle clocks and Global Positioning System (GPS) monitor station reference clocks is performed by the Naval Research Laboratory (NRL), in cooperation with the GPS Master Control Station, under the sponsorship of the GPS Joint Program Office. The measurements are collected by multi-channel GPS receivers located at the Air Force and National Imagery and Mapping Agency (NIMA) monitor stations. The offset of each Navstar clock, computed every 15 minutes, is referenced to the Department of Defense Master Clock. The resultant Navstar clock offsets are then used to compute frequency offset, drift offset, frequency stability profiles, and frequency stability histories. The beginning-of-life, steady state, and end-of-life performance of selected cesium and rubidium atomic clocks is presented. Frequency stability results are presented using sample times that vary from 15 minutes to several days. The stability for sample times of less than one day characterizes the measurement noise, while the stability for sample times in excess of one day characterizes both the periodic effects in the on-orbit data and the long-term performance of the Navstar atomic clocks.*

## **INTRODUCTION**

The year 1999 marks one decade since the launch of the first Global Positioning System Block II space vehicle. During 1989, five Block II space vehicles were placed into orbit, each equipped with four atomic clocks, two cesium and two rubidium. A total of 10 Block II space vehicles were launched into orbit. During the fall of 1990, the launch of Navstar 23 marked the beginning of insertion of Block IIA space vehicles into orbit. The Block II and the Block IIA space vehicles both carried the same configuration of four atomic clocks. In 1997 the first of the Block IIR space vehicles, Navstar 43, was launched and inserted into orbit. The Block IIR space vehicles differ from those in Block II and Block IIA by having only three clocks, all of which are rubidium atomic frequency standards.

In addition to the differences in the configuration of the Navstars in the GPS constellation, there has been an increase in the number of monitor stations used to determine the precise ephemerides. In early 1989, concurrent with the launch of the first Block II space vehicle, NIMA (then the Defense Mapping Agency) assumed responsibility for producing the post-fit ephemerides. Five NIMA monitor stations (Ar-

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gentina, Australia, Bahrain, Ecuador, and England) and five Air Force monitor stations (Ascension Island, Colorado Springs, Diego Garcia Island, Hawaii, and Kwajalein Island) were then operational. By June 1995, eleven monitor stations were available. NIMA had just installed a tracking station at the U.S. Naval Observatory in Washington, D.C. and was able to use as the reference clock the Department of Defense (DoD) Master Clock.

Currently, NIMA uses a total of seventeen monitor stations (five Air Force, eleven NIMA, and one IGS) to determine the precise post-fit ephemerides used in the NRL analysis of clock performance. With these seventeen stations, the precision of both the NIMA solution for the post-processed orbit and the subsequent NRL solution for the Navstar clock offsets have been improved. The additional monitor stations also contribute to an improvement in the common-view time transfer solution using a technique known as multiple-path linked common-view time transfer [1]. The resultant time transfer estimates are used to reference the offset of the Navstar clock from each monitor station back to the DoD Master Clock. Averaging multiple measurements of a Navstar clock offset at a given time results in a precision on the order of one nanosecond. The resulting measurements, known as "continuous coverage" [2], are then used to compute the frequency offset, drift offset, frequency stability profiles, and frequency stability histories for the Navstar clock.

The results to be presented use data collected from 1989 to October 1, 1999. All results are referenced to the DoD Master Clock. Results based on data collected prior to June 1995 are computed using the broadcast ephemerides. The effect on the clock offset determination from the broadcast ephemerides has been previously analyzed [3]. Results presented after June 1995 are computed using the NIMA precise ephemerides.

## FREQUENCY STABILITY MODELS

NRL currently employs two models to measure the frequency stability of the Navstar and monitor station clocks in the time domain. The first, the Allan variance [4], is normally used in the analysis of cesium atomic frequency standards that exhibit extremely low aging. However, with the increased use of rubidium clocks in the Navstars, the Hadamard variance [5] has been adopted because it adaptively removes the very large drift characteristic of rubidium clocks. The presence of such large values of drift would otherwise dominate the estimates of stability even at small sample times. Because the Navstar clocks are expected to operate for years on orbit, an analytical technique, known as the frequency stability history, was developed [6] to analyze frequency stability as a function of time.

## NAVSTAR ATOMIC CLOCK SUMMARY

The clocks on the Navstar Block II, IIA, and IIR space vehicles used are of two types: cesium and rubidium. *Table 1* presents the number of Navstar space vehicles, the number of cesium atomic clocks, the number of rubidium atomic clocks, and the total number of atomic clocks that have been launched into the GPS constellation for each space vehicle block type.

A total of 95 atomic clocks of the Navstar Block II/IIA/IIR configuration have been placed into the GPS constellation as of October 1, 1999. Since that time an additional Block IIR space vehicle, Navstar 46 with three additional EG&G rubidium clocks, has been launched but is not included in this summary. Five manufacturers have made atomic clocks for the Block II/IIA/IIR space vehicles under contract to the GPS Joint Program Office.

*Table 1*  
**(As of 1 October 1999)**

Space Vehicle Block Type	Number of Space Vehicles	Number of Cesium Clocks	Number of Rubidium Clocks	Total Atomic Clocks
II	10	10	10	20
IIA	18	36	36	72
IIR	1	0	3	3

*Table 2* presents a summary of the manufacturers. It should be noted that additional clocks were produced for the Block I space vehicles that are not included in this summary. One clock will be selected from each of the five manufacturers to document typical levels of performance that have been achieved with the Navstar atomic clocks.

*Table 2*  
**Block II/IIA/IIR Clock Manufacturer Summary**

Manufacturer	Clock Type	Total Atomic Clocks
Frequency and Time Systems (FTS)	Cesium	41
Rockwell	Rubidium	46
Kernco	Cesium	3
Frequency Electronics Incorporated (FEI)	Cesium	2
EG&G	Rubidium	3

## NAVSTAR 13 CESIUM CLOCK

The first clock selected for presentation is a cesium atomic clock built by FTS and installed on Navstar 13 which was launched February 14, 1989. This clock was activated in 1989 and has been continuously operated for more than 10 years. The frequency offset history of the Navstar 13 cesium clock (shown in *Figure 1*) used measurements collected by a dual-frequency GPS receiver located at the U.S. Naval Observatory (USNO), where the reference was the DoD Master Clock. The position of Navstar 13 was computed using the broadcast ephemeris. The frequency offset was computed using clock-offset measurements that were separated by one sidereal day. The initial frequency offset was near  $1\text{pp}10^{12}$ . During 10 years of continuous operation, the frequency offset with respect to the DoD Master Clock has gradually decreased to approximately  $-5\text{pp}10^{12}$ . The frequency stability history for this cesium clock is presented in *Figure 2*. Each one-day frequency stability estimate was computed using the Allan variance with a 20-day window width. The frequency stability history indicates an essentially constant trend for the entire 10-year data span

except for a brief excursion after initial operation of Navstar 13. It was concluded that the frequency stability history for this cesium clock was essentially constant and time-invariant for more than ten years. Because the frequency stability history indicates time invariance, all of the data available from July 14, 1989 until October 1, 1999 were used to compute the frequency stability profile presented in *Figure 3*. The measured frequency stability, using the Allan variance as an estimator, for a sample time of one day was  $1.4\text{pp}10^{13}$ . The frequency stability continued to improve for longer sample times with a minimum value of  $5.4\text{pp}10^{14}$  for a sample time of 13 days. For sample times from 13 days to approximately 120 days, the frequency stability exhibits a behavior characteristic of a random walk in frequency. Beyond approximately 120 days, the stability is dominated by the 10 year average drift of  $-1.5\text{pp}10^{15}/\text{day}$ .

## NAVSTAR 19 RUBIDIUM CLOCK

The second clock selected for analysis is a rubidium atomic clock built by Rockwell and installed as one of the four atomic clocks on Navstar 19, which was launched October 21, 1989. This rubidium clock was activated on December 30, 1994 and was operated until September 23, 1999 when it was deactivated—a period of 4.7 years. The results presented are based on measurements taken at USNO using the broadcast ephemeris. The frequency-offset history is presented in *Figure 4*. An initial frequency offset of  $2.5\text{pp}10^{10}$  was calculated. The final frequency offset of this rubidium clock was calculated to be approximately  $1\text{pp}10^{11}$ .

The four-day average drift offset history is presented in *Figure 5*. The drift is defined as the normalized first difference of the frequency. The behavior of the drift can be divided into three phases that correspond to (a) beginning of life, (b) steady state, and (c) end of life. Our analysis of this clock defines the beginning-of-life phase to be from December 30, 1994 through April 20, 1995. The steady state phase is defined to be from April 21, 1995 until June 19, 1999. The end-of-life phase is defined to be from June 20, 1999 until the clock was deactivated on September 23, 1999. During the beginning-of-life phase, the values of the four-day average drift varied by  $8\text{pp}10^{13}/\text{day}$ . During the steady-state phase, the drift estimates varied from  $-3.8\text{pp}10^{13}/\text{day}$  to  $2.6\text{pp}10^{13}/\text{day}$ , except for a brief excursion on August 1, 1995.

The frequency stability history is presented in *Figure 6*. Each frequency stability estimate was computed using the Hadamard variance for a sample time of one day and a window width of 20 days. Superimposed on *Figure 6* are the Navstar 19 eclipse seasons denoted by a series of shaded vertical regions. The eclipse seasons occur semi-annually for all Navstars in the GPS constellation and last for about one month. During each eclipse season, the space vehicle passes through the Earth's shadow for a portion of the orbit. Entrance of the satellite into the shadow causes a decrease in the spacecraft temperature. The frequency stability history indicates a frequency stability of about  $1\text{pp}10^{13}$  during the beginning-of-life phase. A gap in the data separates the beginning-of-life and the steady-state phases. The steady-state frequency stability estimates varied from  $3\text{pp}10^{14}$  to  $1.3\text{pp}10^{13}$ .

The frequency stability profile is presented in *Figure 7*. The frequency stability was computed using the data from April 21, 1995 to June 19, 1999, a span chosen to represent the steady state performance of this clock. The measured one-day frequency stability was  $5.9\text{pp}10^{14}$ . A minimum frequency stability of  $3.9\text{pp}10^{14}$  was measured for a three-day sample time. For sample times larger than three-days, the stability is dominated by a random walk in the frequency, the drift having been removed by the Hadamard variance estimator.

## NAVSTAR 30 CESIUM CLOCK

The third clock selected is a cesium atomic clock installed on Navstar 30 which was launched September 12, 1996. This clock, built by Kernco as an alternate-source provider for cesium clocks, has been continuously operated for more than three years. The frequency-offset history is presented in *Figure 8*. The frequency offset was computed for a sample time of one day using the precise ephemerides generated by NIMA. The initial frequency offset was measured to be  $-3.2\text{pp}10^{12}$  with respect to the DoD Master Clock. The frequency offset then decreased to  $-4.2\text{pp}10^{12}$ , gradually increased over a period of two years to a value of  $1.6\text{pp}10^{12}$ , then remained fairly constant. The drift during the last six months of 1999 has been expressible in  $\text{pp}10^{15}/\text{day}$ .

The frequency stability history of this clock for a sample time of one day is presented in *Figure 9*. During the three years that this clock has been operated, a total of six eclipse seasons have occurred. There is no dependence on the eclipse seasons. The frequency stability, estimated immediately after activation, was  $1\text{pp}10^{13}$ . The frequency stability gradually improves over the lifetime of the clock, reaching a value of  $6\text{pp}10^{14}$  by the end of the reporting period. The frequency stability profile for this clock is presented in *Figure 10* using sample times that vary from one day to 100 days. For a sample time of one day, the frequency stability was estimated to be  $7\text{pp}10^{14}$ . The frequency stability for sample times larger than one day continues to improve and reaches a minimum value of  $5\text{pp}10^{14}$  for a sample time of 10 days. The frequency stability estimates remain near the minimum value for sample times of up to approximately 20 days. This Kernco atomic frequency standard is the most stable cesium clock in the GPS constellation.

## NAVSTAR 31 CESIUM CLOCK

The fourth clock selected for presentation is a cesium atomic frequency standard installed on Navstar 31, which was launched March 30, 1993. The clock was built by FEI as an alternate-source provider for cesium clocks. This cesium clock was activated on April 8, 1993 and was operated for 1.8 years being deactivated on January 18, 1995. The frequency-offset history presented in *Figure 11* used measurements collected by a dual-frequency GPS receiver located at the U.S. Naval Observatory (USNO), where the reference was the DoD Master Clock. The position of Navstar 31 was computed using the broadcast ephemeris. The frequency offset was computed using clock-offset measurements that were separated by one sidereal day. The initial frequency offset was calculated to be  $2.7\text{pp}10^{12}$  with respect to the DoD Master Clock. The frequency offset then increased gradually in a linear fashion to a value of  $3.3\text{pp}10^{12}$  before being deactivated.

The frequency stability history of this clock for a sample time of one day is presented in *Figure 12*. During the 1.8 years that this clock had been operated, a total of four eclipse seasons had occurred. There appears to be no dependence on the eclipse seasons. The frequency stability, estimated immediately after activation, was  $2.2\text{pp}10^{13}$ . The frequency stability hovered between  $1\text{pp}10^{13}$  and  $2\text{pp}10^{13}$  over the lifetime of the clock. The frequency stability profile for this clock is presented in *Figure 13* using sample times that vary from one day to 64 days. For a sample time of one day, the frequency stability was estimated to be  $1.6\text{pp}10^{13}$ . The frequency stability for sample times larger than one day continues to improve and reaches a minimum value of  $4.5\text{pp}10^{14}$  for a sample time of 20 days. The frequency stability attains a value of  $7.0\text{pp}10^{14}$  at a sample time of 64 days.

## NAVSTAR 43 RUBIDIUM CLOCK

The fifth clock selected for analysis is a rubidium atomic clock built by EG&G [5]. This rubidium clock is the first of the next generation of Navstar rubidium atomic clocks. Three of these rubidium clocks were installed on Navstar 43, which was launched and inserted into the GPS constellation on July 23, 1997. One rubidium clock (Serial No. 6) was activated on August 13, 1997 and currently provides the frequency reference for the Navstar 43 navigation signal. Between September 26, 1997 and December 1, 1997 a second EG&G rubidium clock (Serial No. 5) was used to provide the frequency reference. However, power was maintained to both clocks, which is a new capability of the Block IIR design. The analysis used all data available for rubidium clock Serial No. 6, *i.e.*, data collected from August 13, 1997 to October 1, 1999. The frequency-offset history is presented in *Figure 14*. An initial one-day average frequency offset of  $9.6\text{pp}10^{12}$  was calculated. The final one-day average frequency offset of this rubidium clock was calculated to be approximately  $-2.7\text{pp}10^{11}$ .

The four-day average drift offset history is presented in *Figure 15*. The behavior of the drift is characterized by an activation transient followed by asymptotic decay toward zero. The activation transient is defined as the region of rapid change which lasted about one month to September 26, 1999, when the source of the timing signal was switched to rubidium clock Serial No. 5. If the clocks had not been switched, the activation transient would probably have been seen to dominate the behavior for some time into what instead was a gap in the data. The initial value of the four-day average drift was estimated to be  $-2.7\text{pp}10^{13}/\text{day}$ . The final value attained by the drift was estimated to be  $-3.2\text{pp}10^{14}/\text{day}$ .

The frequency stability history is presented in *Figure 16*. Each frequency stability estimate was computed using the Hadamard variance, a sample time of one day, and a window width of 20 days. Superimposed on *Figure 16* are the Navstar 43 eclipse seasons denoted by a series of shaded vertical regions. The frequency stability history indicates a frequency stability of about  $2.2\text{pp}10^{14}$  during the activation transient. A gap in the data separates the activation transient and the steady-state behavior. The steady-state frequency stability estimates hovered close to  $2.0\text{pp}10^{14}$ .

The frequency stability profile is presented in *Figure 17*. The frequency stability was computed using the data from December 4, 1995 to October 1, 1999, a span chosen to represent the steady state performance of the clock. The frequency stability was calculated for sample times of one to 66 days. The stability for a sample time of one day was estimated to be  $2.2\text{pp}10^{14}$ . A minimum frequency stability of  $5.2\text{pp}10^{15}$  was estimated for a sample time of eight days. For sample times larger than about 20 days, the stability is dominated by a random walk in the frequency, the drift having been removed by the Hadamard variance estimator. This clock is the best performing frequency standard in the GPS constellation.

## SUMMARY

The location of the space vehicles in the constellation by plane and by slot, *i.e.*, by position in the plane, is shown in *Figure 18* for the constellation as it was configured on September 30, 1999. The shaded cells indicate that cesium clocks were the source of the timing signal for the respective space vehicles. The unshaded cells denote that the source of the timing signal for the respective space vehicles were rubidium clocks.

In Figure 19 is shown the frequency stability profiles for the clocks on all 27 of the Navstar space vehicles constituting the GPS constellation on September 30, 1999. The frequency stability was estimated for sample times of one day to 12 days. The Hadamard variance was used to estimate the stability for all clocks, both cesium and rubidium. For the low-drift cesium clocks, the Allan and Hadamard variances are essentially identical. The frequency-stability profile for the Navstar 43 rubidium clock can be seen to be superior to that of all the other clocks.

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# NAVSTAR 13 CESIUM FTS

**NAVSTAR 13 TIMING SIGNAL CORRECTED FREQUENCY OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. 14  
Broadcast Ephemeris**

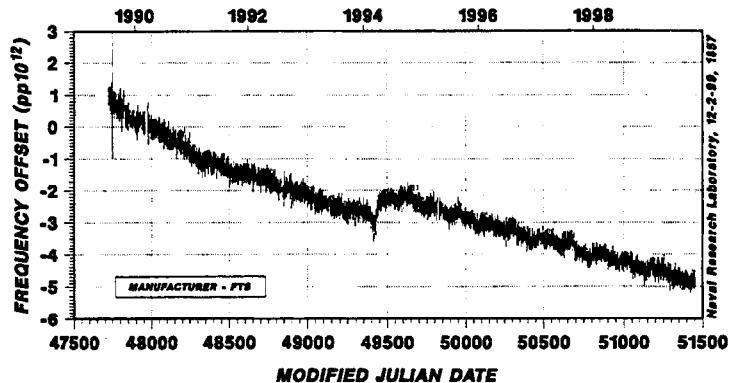


Figure 1.

**FREQUENCY STABILITY HISTORY OF NAVSTAR 13 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. 14  
Sample Time: 1 day Window Width: 20 days**

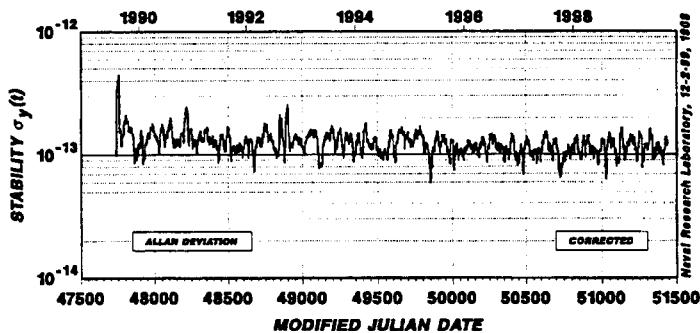


Figure 2.

**FREQUENCY STABILITY OF NAVSTAR 13 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. 14  
14-JUL-99 to 1-OCT-99**

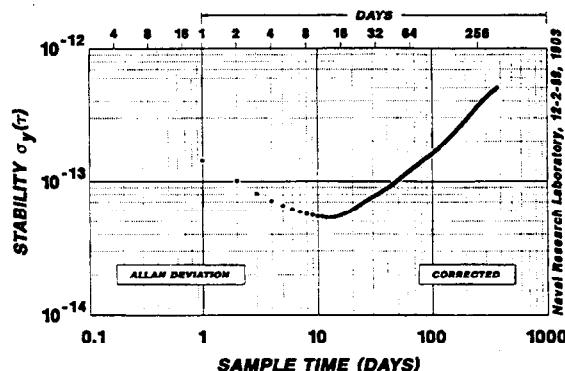


Figure 3.

# NAVSTAR 19 RUBIDIUM

## Rockwell

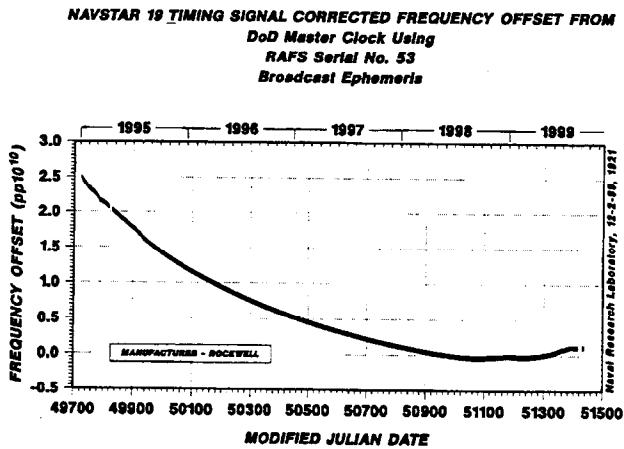


Figure 4.

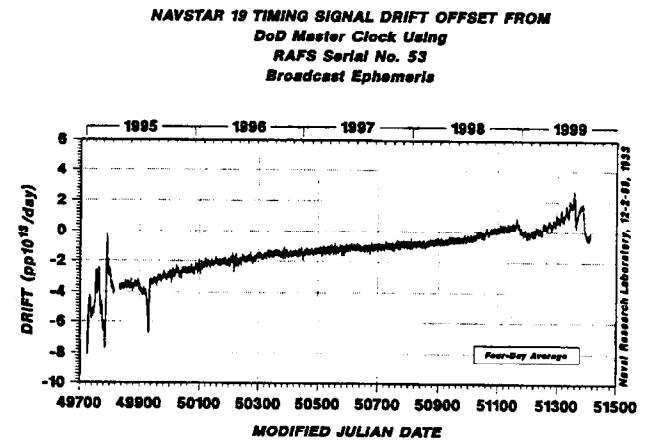


Figure 5.

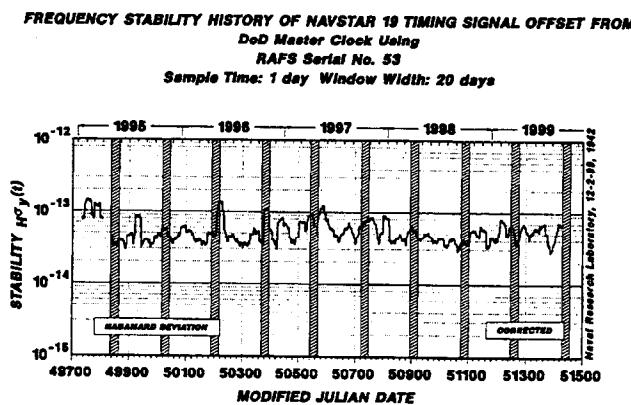


Figure 6.

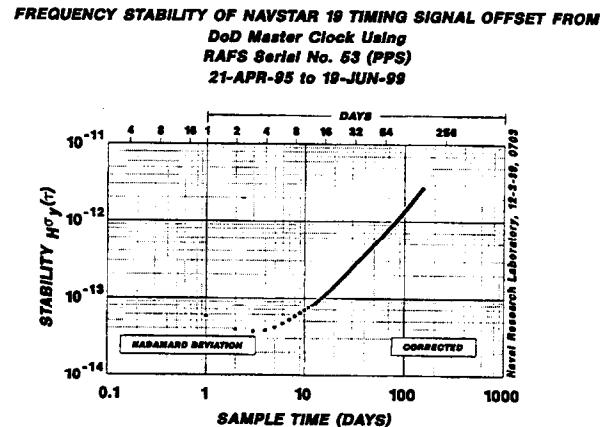


Figure 7.

# NAVSTAR 30 CESIUM

## Kernco

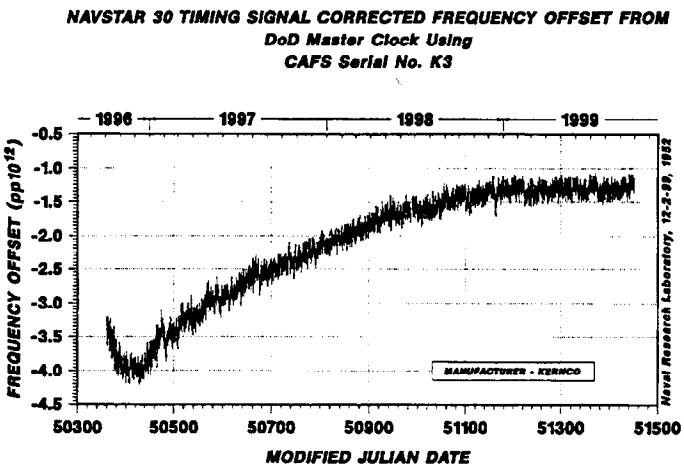


Figure 8.

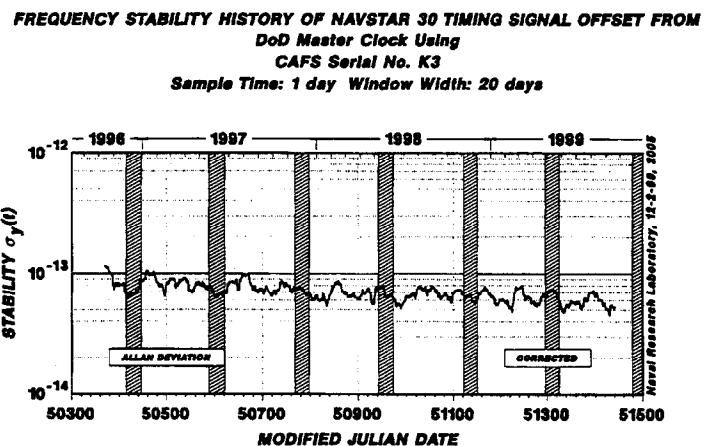


Figure 9.

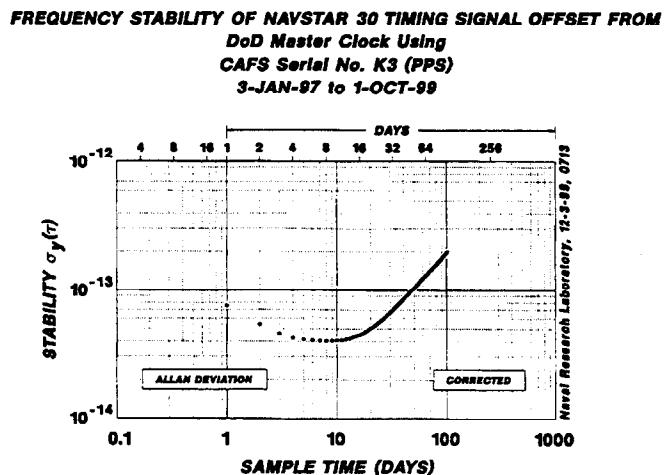


Figure 10.

# NAVSTAR 31 CESIUM FEI

**NAVSTAR 31 TIMING SIGNAL CORRECTED FREQUENCY OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. F6  
Broadcast Ephemeris**

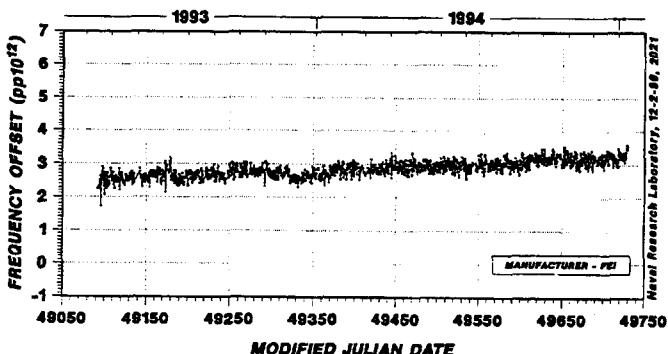


Figure 11.

**FREQUENCY STABILITY HISTORY OF NAVSTAR 31 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. F6  
Sample Time: 1 day Window Width: 20 days**

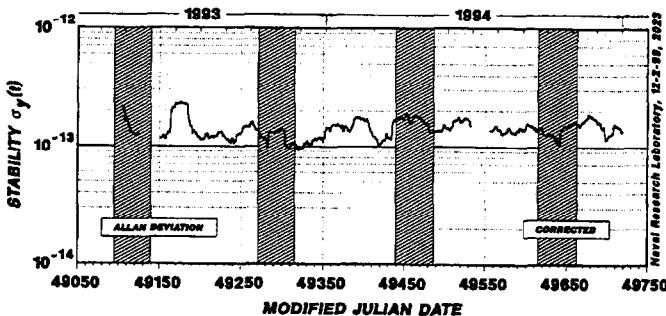


Figure 12.

**FREQUENCY STABILITY OF NAVSTAR 31 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
CAFS Serial No. F6  
14-APR-93 to 14-JAN-95**

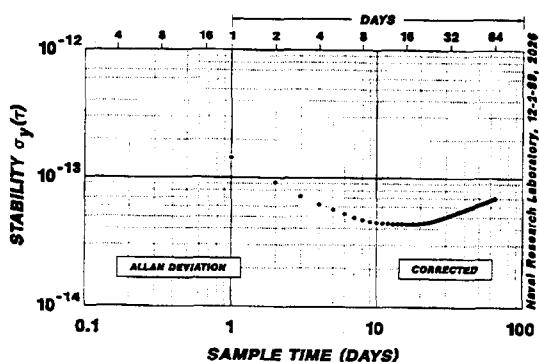


Figure 13.

# NAVSTAR 43 RUBIDIUM EG&G

**NAVSTAR 43 TIMING SIGNAL CORRECTED FREQUENCY OFFSET FROM  
DoD Master Clock Using  
RAFS Serial No. 6**

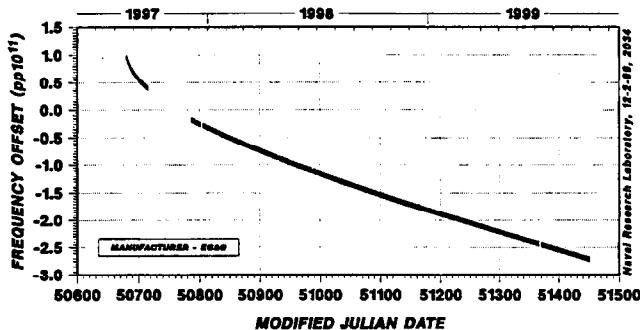


Figure 14.

**NAVSTAR 43 TIMING SIGNAL DRIFT OFFSET FROM  
DoD Master Clock Using  
RAFS Serial No. 6**

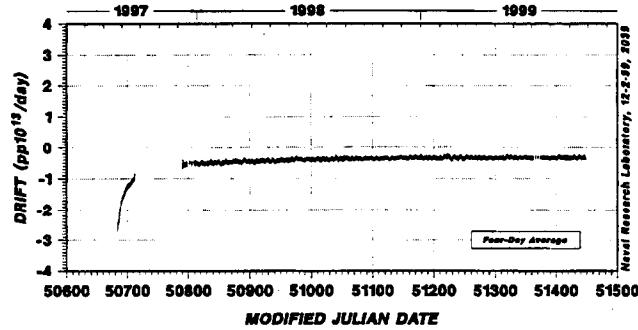


Figure 15.

**FREQUENCY STABILITY HISTORY OF NAVSTAR 43 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
RAFS Serial No. 6**  
Sample Time: 1 day Window Width: 20 days

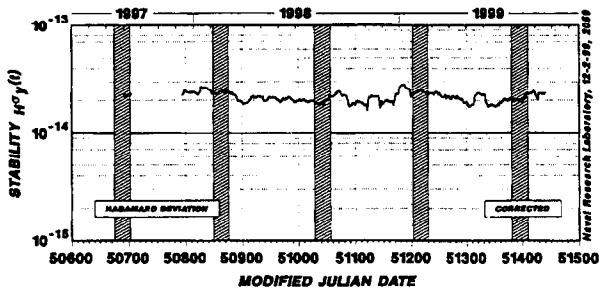


Figure 16.

**FREQUENCY STABILITY OF NAVSTAR 43 TIMING SIGNAL OFFSET FROM  
DoD Master Clock Using  
RAFS Serial No. 6**  
4-DEC-97 to 1-OCT-99

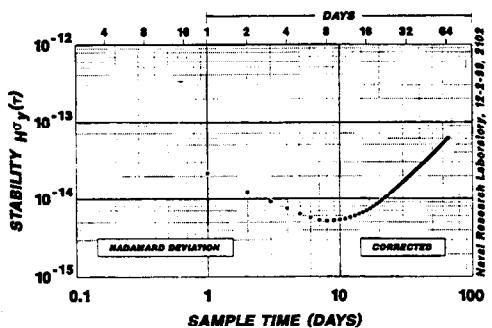


Figure 17.

# COMPOSITE NAVSTAR RESULTS

(1 April 1999 to 1 October 1999)

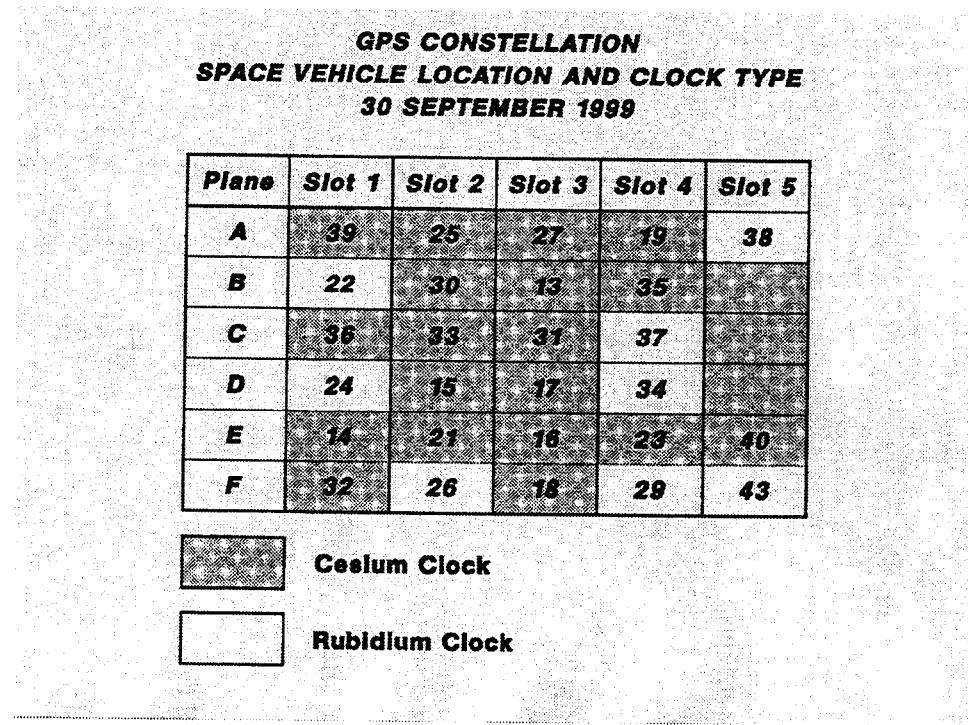


Figure 18.

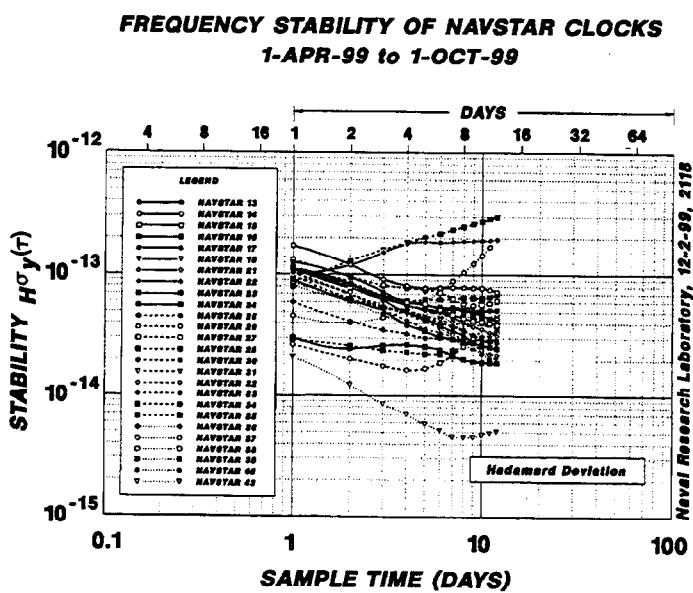


Figure 19.

## Questions and Answers

DAVID ALLAN (Allan's Time): I would like to congratulate you on an outstanding paper; it is something that is needed for GPS and highly recommended for Galileo. One comment I would like to make is that in regard to diagnostics for the satellite, this is extremely important because two clocks measured against each other on board have essentially zero noise; whereas when you're doing diagnostics from the ground, you have all of the ionosphere and propagation problems which contaminate how well you know the system. So the diagnostic tool is also extremely important, I believe.

JAY OAKS (NRL): Does this mean you have to have two atomic standards in operation at all times for this to work?

VICTOR REINHARDT (Hughes): Well, yes. In order to compare two standards, they both have to be on, so the price you're paying is you're running second unit.

OAKS: So then the considerations that come to mind are the power required to run two standards in orbit and does this defeat some of the lifetime of the overall —

REINHARDT: Yes. There are certain scenarios you can use. You of course have to have the spare power. I don't think that is a major issue for the satellite. But you can have a compromise situation where you're looking at the clock and if you have any hint that there might be a problem, you turn it on. Also, in reference to what Dave Allan said, what I recommend is that, even if you don't have a second standard on, you monitor the diagnostics. If you have a phase-lock loop unit, look at what's going on; look at the phase difference, that phase error with high resolutions. Because even monitoring the atomic standard relative to the VCXO can give you information about what's going on. So for short-term measurements, at least, you can use the VCO as a flywheel.

ALLAN: We need to remind ourselves that IIR has a hot backup, but does not have the measurement capability. It has the clock on, but you can't do what you could do if you have the system.

REINHARDT: Yes, yes.

ALLAN: The power's being used and you're wasting the power without having a good measurement system.

OAKS: I was thinking of the older spacecraft.

REINHARDT: Yes, so I would encourage this. I think NRL is, in fact, talking about some sort of measurement system that they're developing. You know, there are many, many ways to implement this kind of thing. The ultimate is the seamless switchover, because then you have a completely transparent system. But I think the second best, which is quite close, is just to have some sort of measurement system on board that, when you do have two units on, you can measure them; and also, measure them relative to the crystal.

DEMETRIOS MATSAKIS (USNO): There's another way to handle the switchover, which would be just to tell the Kalman filter that you have a new clock and have it adjust right away. It's a matter of expense, I guess, and other issues like that.

REINHARDT: Yes, that would be a good way to do that. What you do see is a change in the

phase in the frequency, but of course the prediction is good.

MATSAKIS: Yes, but you don't have to wait for the filter to learn it. You can just tell it right away.

REINHARDT: But in order to do that, you need a measurement system to look at that second unit. So you do need the measurement system on board to do that. And, yes, that would solve the acquisition problem. So the key here, if I can get one message across, is the measurement system is the most important part of, I think, improving the availability of GPS in case of clock problems.-